SUBMM WAVE SUPERCONDUCTING HOT-ELECTRON DIRECT DETECTORS

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ABSTRACT

We are developing a new type of hot-electron direct detector (HEDD) which employs a weak electron-phonon coupling in superconducting microbridges. Such a detector with a potential NEP $\approx 10^{-20}$ W/$\sqrt{\text{Hz}}$ at 0.1 K will meet the needs for future background-limited arrays on space telescopes. The HEDD is based on a 1-micron-size transition edge sensor fabricated from an ultra-thin film of a superconductor with T_c = 0.1-0.3 K. The strong temperature dependence of the electron-phonon coupling in disordered superconductors allows for adjustment of the electron-phonon scattering time to the desirable value of ~ 1 ms. Current effort is aimed at the demonstration of the feasibility of such a detector at 0.3 K where the NEP $\approx 10^{-18}$ W/$\sqrt{\text{Hz}}$ and the time constant ~ 1 μs are expected. The radiation frequency response of a prototype antenna-coupled Nb device has been measured and proved to be flat over the range 250-900 GHz. The fabrication technology for a few-μm-long HEDD devices using thin Ti films has been developed and the first output noise measurements data are presented. The results indicate good agreement with the hot-electron model.

MOTIVATION AND BACKGROUND

Recently, we have presented a concept for a hot-electron direct detector (HEDD) capable of counting single millimeter-wave photons [1]. Such a detector meets the needs of future space far-infrared applications (NEP $\leq 10^{-19}$ W/$\sqrt{\text{Hz}}$) and can be used for background-limited detector arrays on missions like SPIRIT, 10-m filled aperture telescope, SAFIR, and SPECS [2]. The detector is based on a microbridge transition edge sensor fabricated from an ultra-thin film of a superconductor with the critical temperature T_c = 0.1-0.3 K. The sensor is a radiation absorber at the same time. Since it is made from a thin disordered film its normal resistance is large (~50 Ω) and is suitable for matching to a planar microantenna. A very strong temperature dependence and the electron-mean-free-path dependence of the electron-phonon coupling allow for adjustment of the electron-phonon scattering time, $\tau_{e\text{-}ph}$, in Hf and Ti films to the desired value ~ 1 ms at T = 0.1 K [3]. The microbridge contacts need to be made from a superconductor with a higher critical temperature (Nb); these contacts will block the thermal diffusion of hot carriers into the contacts because of the Andreev reflection [4]. The low electron-phonon heat conductance, high thermal resistance of the contacts, and small heat capacity of electrons in a micron-size bridge determine the noise equivalent power of ~ 10^{-20} W/$\sqrt{\text{Hz}}$ at T = 0.1 K and ~ 10^{-18} W/$\sqrt{\text{Hz}}$ at T = 0.3 K, which is correspondingly 100 and 10 times better than that of state-of-the-art bolometers. By exploiting the negative electro-thermal feedback [5], the

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detector time constant can be made much shorter than bare $\tau_{e\text{-}ph}$, ie. ~ 0.1 ms at 0.1 K and ~ 1 μs at 0.3 K without sacrificing sensitivity. As well as for the other TES's, a dc SQUID is the most suitable readout amplifier for the HEDD. A typical noise of the state-of-the-art SQUIDs (~ 1 pA/√Hz) will be smaller than that of the HEDD itself [1].

With the HEDD technology in hand, one can envision great opportunities for advance imaging arrays. The use of planar antennas for coupling of micron-size bolometers to submillimeter radiation and bulk (Si, sapphire) substrates would allow for a small size array chip. Indeed, one detector element would occupy as little as ~100×100 μm^2 area on Si. So, a 100×100 array chip would have a 1×1 cm^2 size. Since the illumination of the HEDD monolithic detector array has to be done from the back of the chip the array can be integrated with a multiplexer chip using a well established indium bump bonding technique routinely used at wavelengths between 1 and 30 μm.

Our current effort is aimed at the demonstration of the feasibility of the HEDD at submillimeter waves. We have addressed the issue of the spectral response in HEDD, have developed fabrication technique for short Ti devices, have performed first dc and noise tests of subkelvin HEDDs and are currently working towards fabrication of a fully functional antenna-coupled HEDD operating at 0.3 K. The results of the work are presented in following sections.

SPECTRAL RESPONSE IN HEDD

Spectral response of a bolometer is usually determined by the spectral behavior of the absorber and by the input circuit (antenna, filters etc.). For a normal metal absorber the spectral characteristic shows weak variations with frequency. The same is true for a superconducting absorber if the radiation frequency is larger than 2Δ (Δ is the superconducting gap in the bolometer material). In HEDD, the small sensor size is the key to the high sensitivity. At low temperature, however, the diffusion length of quasiparticles at 0.1 K is much longer than the device length, so Andreev contacts should be used to prevent the escape of thermal quasiparticles [4]. All non-equilibrium quasiparticles excited up to the frequency $\nu_c = \Delta_c/h$ (Δ_c is the gap in the Andreev contacts) are confined within the sensor area. For higher frequencies, the quasiparticles with energy greater than Δ_c may, in principle, diffuse out before they relax to the gap (Δ_c) energy, and recombine in the contacts. In this case, a part of the signal energy may be lost via recombination and emission of $2\Delta_c$-phonons and will not contribute to the change of the bolometer resistance. The effect would have a spectral threshold at ν_c. This effect is only important if quasiparticles have time to reach the contacts before they scatter via electron-electron interaction and reduce their energy to the value below Δ_c. A fraction of the device length affected by this process is $L_c \approx [D\tau_\varepsilon(\Delta_c)]^{1/2}$ where D is the electron diffusion length, $\tau_\varepsilon(\Delta_c)$ is the effective energy relaxation length at the edge of the energy gap in the Nb contacts (T_c ~ 9K). Since $\tau_\varepsilon \sim \varepsilon^{-n}$ ($n \geq 2$) at high energies, the quasiparticles excited above Δ_c will have the diffusion length shorter than L_c. The estimates [1] done under an assumption that τ_ε is determined by the electron-electron scattering only show that $L_c \approx 100$ nm in dirty films. Thus, in principle, a 1-μm-long device can be long enough to make the above process ineffective. This is, however, a situation that has never been studied experimentally, so we performed direct measurements of the spectral response.

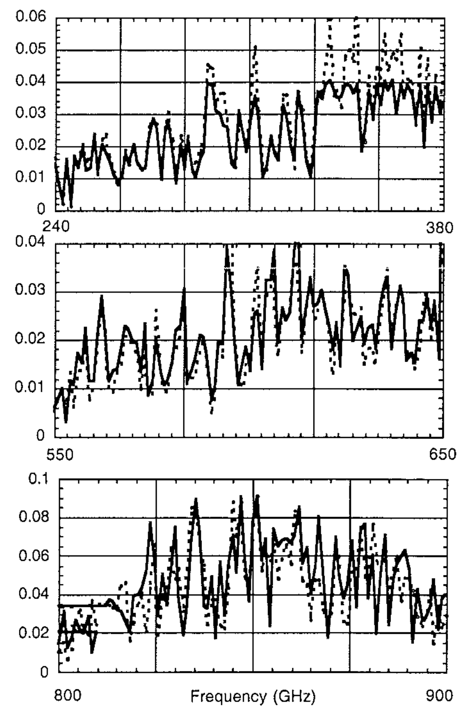

Figure 1: Submillimeter spectra of a Nb HEDD measured at two temperatures: dots—4.2K, solid—8.4K. Vertical axis shows the response in arbitrary units.

We used prototype antenna-coupled HEDD devices fabricated at JPL. 1-μm-long bridges were made from a 12 nm thick Nb film with $T_c = 6.5$ K. The contacts were made from a 100 nm thick Nb film with $T_c \approx 8.6$ K. The devices were fabricated on a Si substrate with a planar spiral antenna whose operating range was between 100 GHz and 3 THz. The detector assembly also included an elliptical Si lens to focus the incoming radiation onto the antenna. A Si chip with the antenna was mounted on the back side of the lens so the antenna was in the rear focus of the lens. The response of the detector to radiation produced by continuously tuned backward-wave-oscillators (BWO) was measured. Three BWOs were used to cover the range 250-900 GHz. In order to perform *in situ* normalization of the response, measurements at two different temperatures were made for each frequency (see Fig. 1). First temperature was 4.2 K at which the device was biased to the state where the resistance was close to the normal and the absorption in the bridge was uniform and practically frequency independent. The electron temperature in the sensor is close to the critical temperature of the film, i.e. 6.5 K. At the same time, the gap in the contacts (which were at 4.2 K) was fully open. The second temperature was 8.4 K and the bridge itself was in pure normal state. The contacts, however, were in the resistive state with practically zero gap. The absorption of the radiation occurred again in the bridge but the detection of the temperature rise was in the contacts which were biased at the edge of their superconducting transition. In the second case, no frequency dependence should be expected since there was no gap in the contacts. If the spectrum at 4.2 K showed a decrease of the response with frequency above ν_c, that would indicate a potential problem with the loss of quasiparticles. Figure 1 shows two spectra in a broad frequency range. The bandgap in Nb contacts $\nu_c \approx 330$ GHz lies within this range. As one can see, there is no noticeable difference between two spectra. This result indicates that it is unlikely that diffusion of hot quasiparticles is important in micron-size HEDD sensors made from dirty superconductors. This conclusion applies to subkelvin HEDDs: the gap in the contacts would be the same in any case and diffusivities of dirty Ti, Hf and Nb films are all of the order of 1 cm^2/s.

FABRICATION AND CHARACTERIZATION OF Ti MICROBRIDGES

DC measurements.

Titanium has been previously identified as a good candidate material for an HEDD operated at 0.3 K [3]. We fabricated simple Ti microbridges to test the quality of the material and the operability of our dilution refrigerator test system with a SQUID. The devices were fabricated at Rutgers University with a final removal of the protection gold layer done at JPL. 20 nm thick films grown by magnetron sputtering on sapphire substrate were used. The films were patterned into 1-μm-wide, 0.5-to-3-μm-long microbridges. No superconducting (Nb) contacts were fabricated at this time. Most of bridges exhibited sharp superconducting transition ≈ 10 mK wide. The critical temperature was in the range 0.3-0.36 K and the normal state resistance was 40-50 Ohm for longest bridges.

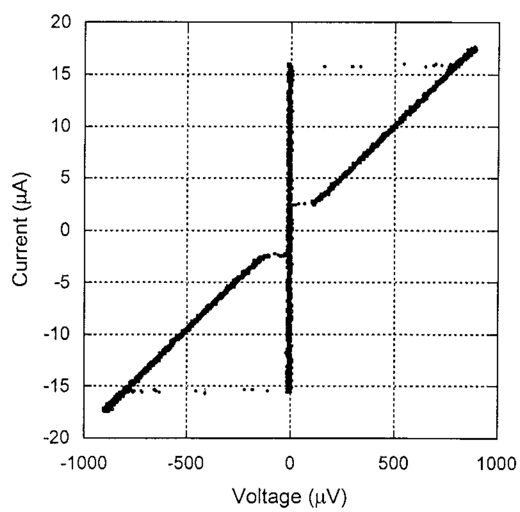

Figure 2: The IV characteristic of a 3-μm-long Ti bridge at 100 mK.

Figure 2 demonstrates a current-volatge (IV) characteristic of a typical bridge at 100 mK. The critical current is rather large and a strong hysteresis due to self-heating is observed. The position of the drop-back point on the IV-curve did not depend on the temperature and allowed us to estimate the effective thermal conductance of the bridge using a simple heat balance equation: $P = \gamma V\left(T_c^2 - T^2\right)/\left(2\tau_{diff.}\right)$ Here γ is the Sommerfeld constant, V is the bridge volume, P is the Joule power. The diffusion time derived from this expression $\tau_{diff.} \approx 3$ ns agrees well with the theoretical value calculated as $\tau_{diff.} = L^2/(12D)$ with D =2.4

cm^2/s. If the contacts were made from Nb the heating would be defined by the electron-phonon relaxation which is much slower process for given conditions ($\tau_{e\text{-}ph} = 20$ μs at 0.3 K [3]).

Noise measurements.

The output noise of a microbridge was measured when the device was voltage biased at a temperature somewhat below T_c where a negative differential resistance was seen. A Quantum Design dc SQUID amplifier connected in series with the bridge was used for the measurements. A 1-Ω resistor in parallel to the device+SQUID chain provided sufficient voltage bias. An example of the data set taken at 338 mK is shown in Fig. 3. Solid dots is experimentally measured noise for different bias voltages. The noise was highest when the bias point was right on the top of the IV characteristic. The noise of the circuit loop with the device in the normal state was 2 pA/Hz$^{1/2}$. The variation of the noise vs bias agrees with what might be expected from a hot-electron mechanism with diffusion cooling. Assuming that the shape of the IV characteristic is defined by self-heating only, the thermal energy fluctuation (TEF) noise (dotted line) and the Johnson noise (dashes) were calculated. The experimental points are within a factor of 2 from the theoretical curve and demonstrate the same trend with the bias. Another indication of the diffusion cooling is a very large noise bandwidth. Actually, no difference in the shape of the noise spectra was seen up to the instrumentation limit of 100 kHz. The TEF noise cuts off at the frequency roughly corresponding to the inverse temperature relaxation time (with some modification due to self-heating effects). In our case, the bare temperature relaxation time is already just a few nanoseconds, so the corresponding bandwidth would be several tens of MHz. The NEP calculated from the experimental data is rather high (~ 10^{-16} W/Hz$^{1/2}$) that is exclusively due to the fact that the current devices are too fast.

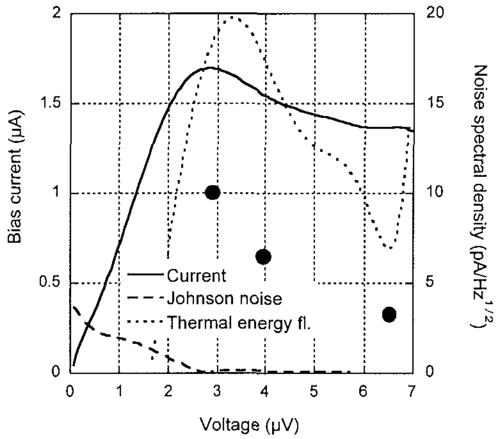

Figure 3: Output noise data at 338 mK. Circles— experimental points, dashes and dots — hot-electron model calculations.

CONCLUSION

In this work, we have demonstrated that a micron-size HEDD has a frequency independent response in the submillimeter waverange. A fabrication routine has been developed for Ti HEDD yielding good quality devices. The output noise of Ti HEDD devices explains well by the hot-electron model. Augmentation of Nb contacts to Ti microbridges is currently in progress and should bring us soon to the level where a test antenna-coupled HEDD at 0.3 K can be started.

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